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Abstract. Nucleosynthesis of heavy nuclei in metal-poor stars is generally ascribed to the r-process, as the abundance pattern in many such stars agrees with the inferred Solar r-process abundances. Nonetheless, a significant number of these stars do not share this r-process template. We suggest that many such stars have begun an r-process, but it was prevented from running to completion in more massive stars by collapse to black holes, creating a "truncated r-process," or "tr-process." The observed fraction of tr-process stars is found to be consistent with expectations from the initial mass function (IMF), and we suggest that an apparent sharp truncation observed at around mass 160 could result from a combination of collapses to black holes and the difficulty of observing the higher mass rare earths. We test the tr-process hypothesis with calculations that are terminated before all r-process trajectories have been ejected. These produce qualitative agreement with observation when both black hole collapse and observational realities are taken into account.

Introduction

The r-process synthesizes half the nuclides heavier than iron, all of the nuclides heavier than ^{209}Bi, and is primary, i.e., its nucleosynthesis does not to depend on preexisting nuclides [1-4]. Furthermore, its production of heavy nuclides in many metal poor stars appears to be quite uniform [5], and it also produces relative r-process abundances that are similar to those inferred for the Solar system. A standard r-process model suggests that it occurs in the neutrino driven wind that emanates from core-collapse supernovae (CCS) [2, 6, 4], although that scenario is not without its issues (see ref. [7]). However, there are also possible solutions to these difficulties, e.g., sterile neutrinos that might yet make this r-process site viable.

A subset of metal poor stars exhibits some features of the r-process, but their abundances represent a poor match with the “standard” abundance template [8-10], frequently identified as that of CS-22892-052 [5]. One data set [10] suggests that a distribution of r-process abundances exists in metal poor stars, with some resembling the standard template, but with a significant fraction having abundances that do not. These latter stars appear to favor the lighter r-process nuclides, and many have abundances that terminate around mass 160 u.

We suggest that these latter patterns could be produced by stars whose cores first collapse to neutron stars but then collapse to a black holes from subsequent infall - so called “fallback supernovae.” Such stars span a mass range from roughly 25 to 40M_o [11]. When the collapse to the black hole occurs, the r-process enrichment of the ISM terminates either when the r-processed regions are consumed by the black hole or when the electron antineutrinos fall below the event horizon [12]. The tr-process enrichment of the ISM would end at different stages, depending on the precise time at which the black hole terminated the r-process production. We suggest that the delayed collapse to the black hole, combined with the difficulties in observing the higher mass rare earths, could produce the cutoff in the r-process distributions observed around 160 u.

The scenario we envision assumes that mass elements that predominantly produce the lighter r-process nuclei are ejected before the mass elements that produce the heavier r-process nuclides. Any setting within a CCS that satisfies this condition would allow for a tr-process. To evaluate this idea quantitatively we apply the neutrino-driven wind model for the r-process. Although not without issues, this model is plausible and well discussed in the literature and makes a good setting for discussing the tr-process.

Neutrino-Driven Wind Model of the r-Process

In this model, neutrinos from the nascent neutron star heat its surface material and drive it away in a wind. The wind element then expands and cools and its nucleons assemble into heavier nuclei, which serve as the seeds for the subsequent r-process [2]. The abundances of the seed nuclei are well-described by a quasi-equilibrium which, for typical entropies and neutron richness of neutrino-driven wind environments, have an abundance peak near A=100. As the temperature in the element decreases, charged-particle reactions freeze out. In a high neutron density environment the resulting seed nuclei will be promoted to higher mass by successive neutron captures and β-decays. This flow slows at the neutron closed shells at 82 and then 126 neutrons, producing the r-process abundance peaks at A=130 and 195 u [2, 13].

The neutrino-driven wind occurs over several seconds. In the standard scenario [14, 6, 2], the wind elements that leave the star early have lower entropy and neutron richness than those that leave later. It is in the later departing elements that the heaviest nuclei are made. Thus, if the neutron star collapses to a black hole after the lower-entropy elements leave the star but before the higher-entropy elements do, the r-process will be truncated, and the abundance pattern will be dominated by lighter r-process nuclei.

Current CCS models do not naturally produce the entropy or the neutron richness required for a successful r-process. While CCSe may not be the site of the r-process, it may also be that current CCS models are not yet sufficiently detailed to properly describe the CCS parameters. For example, results from multi-dimensional hydrodynamics calculations suggest that the instabilities resulting from those calculations may ultimately be shown to produce the entropy required for making the heaviest r-process nuclei [15]. It will also be necessary to include all of the detailed neutrino physics to characterize the neutron richness in matter expelled from the CCS. Future work will determine whether more advanced CCS models will provide the conditions needed for the r-process. For the purposes of the present paper, we assume that neutrino-driven winds in CCSe are at least one site of r-process nucleosynthesis.

Model Calculations

To study tr-process nucleosynthesis, we applied the basic idea of Woosley et al. [2], who assumed that the r-process occurs in the neutrino driven wind from a CCS. In that study, a succession of 40 “trajectories” (thin shell wind elements), all originating within the (spherically symmetric) star, but having different initial density, temperature, entropy, and electron fraction, were emitted from the star, thus contributing to the total r-process nucleosynthesis. The bubble evolved in time, so that the conditions under which the individual trajectories were processed changed with the identity of the trajectory. We also assumed that the subsequent trajectories ceased when the collapse to the black hole occurred. This would be consistent with [2] in which successive trajectories were assumed to generate a good representation of the Solar r-process abundances.

Our calculations used a network code based on libnucnet, a library of C codes for storing and managing nuclear reaction networks [16]. Data for the calculations were taken from the JINA reaclib database [17]. We performed calculations for trajectories 24 - 40 in the ref. [2] hydrodynamics model. For each trajectory, reaction network calculations were performed for $T_9 < 2.5$ using initial abundances from [2]. Our calculations were simplified by assuming an initial abundance of massive nuclei from a single nuclear seed of mass equal to the average mass at $T_9=2.5$ and an atomic number derived from the average mass number, the Y_e, and the neutron and alpha mass fractions at $T_9=2.5$ in [2]. This is justified by the sharply peaked heavy-nuclide distribution near $T_9=2.5$. An adiabatic expansion was assumed for each trajectory, with entropy constant within a trajectory but varying between trajectories, again consistent with [2], for times for which $T_9 < 2.5$. The material expanded at constant velocity on a time scale consistent with that from ref. [2]. Each calculation was continued until the abundance distribution versus mass had frozen out. Our representation of the full r-process did produce the 130 and 195 u r-process peaks.

The simulation [2] that produced a good r-process representation summed the nucleosynthesis yields from trajectories 24 through 40. We also began with trajectory 24, and performed a mass weighted sum of the nucleosynthesis from trajectories up to some higher number to observe the total nucleosynthesis when the trajectories beyond our maximum trajectory were terminated by the black hole. The results are shown in Fig. 1. There it is seen that truncating the r-process at increasing trajectory number terminates it at increasingly higher mass. Although the curve representing trajectories 24 through 31 does reach the mass 195 u peak, the abundances in that region are nearly two orders of magnitude below that of the full r-process, which would produce an apparent termination at about 140 u.

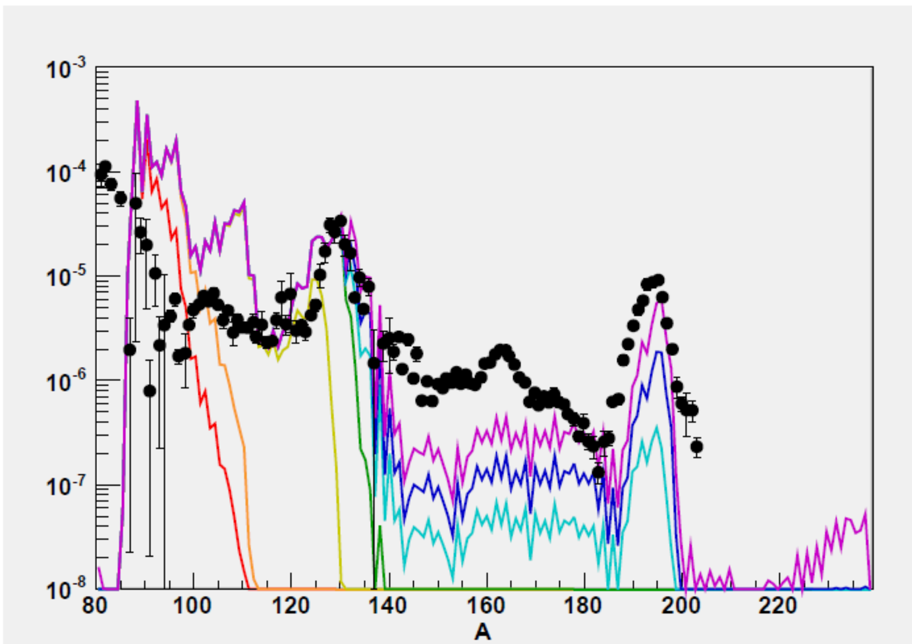

Figure 1. r-Process calculations using the ref. [2] trajectories, but summing results from trajectory 24 to some later trajectory. The successive curves include trajectory 24, 24—26, 24—28, 24—30, 24—31, 24—32, and 24—40. The sums to higher trajectories make both the mass 130 and 195 r-process peaks, and the sum through trajectory 40 comes closest to representing the Solar r-process abundances [18], shown as the dots.

In Fig. 2 we compare several tr-process calculations with the elemental abundances observed in the metal poor halo star HD 122563. This star ([Fe/H] = -2.7) is deficient in the heavy neutron-capture elements (Ba and heavier) relative to the light neutron-capture elements (Sr through Cd) when compared with the scaled Solar r-process pattern, producing a poor match to that pattern. Its abundances matche the scaled Solar r-process pattern better up to an atomic number of about 70, but even this fit is unsatisfactory [19,20]. Stars like HD 122563 may be candidates for enrichment by the tr-process. Fig. 2 shows that the tr-process predictions do reproduce the downward trend in abundance with increasing atomic number seen in some metal poor stars. More study of tr-process calculations is obviously needed, but the general trend is encouraging.

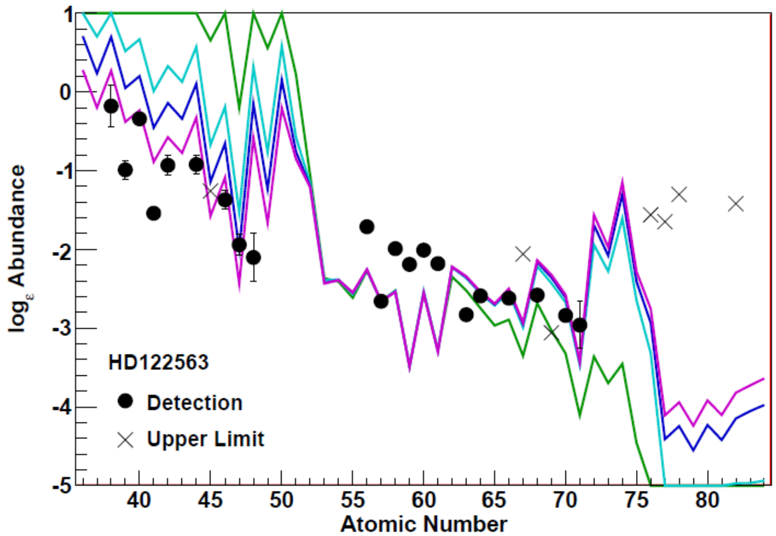

Figure 2. Comparison of tr-process predictions, using the formalism adapted from ref. [2], for three truncation times with abundances in the metal-poor star HD 122563. Data are from refs. [20-22], and the predictions are scaled to the Ba abundance (Z=56).

Probability of Occurrence of tr-Process Stars

In principle, a test of the tr-process model would be provided by a large set of data for metal poor stars that spans the masses of the nuclides produced in the r-process from ~80 u to the heaviest r-process nuclides. Unfortunately this is challenging due to the difficulty of observing the higher mass rare-earth nuclides A > 160 u. Thus all r-process events that terminate between 160 u and lead would appear to terminate at mass 160, giving the effect observed in ref. [12].

Assuming that stars from 8 to 40 M_o produce comparable amounts of r-process material, we used the Salpeter [23] IMF to estimate the fraction of stars whose r-process may be truncated by collapse to a black hole. For this IMF, $dN/dm \propto m^{-2.35}$ for massive stars, where m is in units M_o, and N is the number of stars of a given mass per unit volume. The ratio of the number of stars that would be expected to collapse to black holes (25-40 M_o) to those expected to collapse to neutron stars (8-25 M_o) was found to be 0.13 in a well-sampled IMF.

While a number of r-process rich stars (i.e., stars with [Eu/Fe] > +1.0) have been studied in detail, they form a relatively small fraction of all metal-poor stars. Relatively unbiased samples [24.25] find that stars with [Eu/Fe] > +1.0 comprise <10% of all stars with [Fe/H] < -2.0. Fig. 11 of ref. [10] suggests that stars with [Eu/Fe] < 0 are candidates for enrichment by a tr-process. However, Eu in metal-poor stars with [Eu/Fe] < 0 is difficult to detect. Ba is more easily detected and may be used to represent Eu and other heavy elements in stars lacking s-process enrichment. From the Ba abundances in the large survey of ref. [25] we estimate a lower limit of ~55% of metal-poor stars as candidates for enrichment by a tr-process. Although this is much higher than the 13%

derived from a Salpeter IMF, massive stars with short lifetimes will dominate the chemical enrichment at early times, so the tr-process may well have been a major source of heavy nuclei at these epochs. However, other nucleosynthesis modes (see ref. [7]) may have combined with the tr-process to perform the chemical enrichment of the early Galaxy.

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